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Specific Absorption Rate Evaluation for Passengers Using Wireless Communication Devices Inside Vehicles With Different Handedness, Passenger Counts, and Seating Locations

Sai-Wing Leung*, *Senior Member, IEEE*, Yinliang Diao, *Student Member, IEEE*, Kwok-Hung Chan, *Member, IEEE*, Yun-Ming Siu, and Yongle Wu

Abstract—Radiation from mobile phones inside vehicles, which are semiopen metallic enclosures with irregular shapes and apertures, has been a major concern and has warranted investigation in past years. In this paper, the specific absorption rate (SAR) induced in mobile phone users inside a vehicle was evaluated using different scenarios, including handedness, passenger counts, and seating locations. A computer simulation for SAR distributions in a human body was performed based on the finite-difference time-domain method. The SAR values in mobile phone users in free space were also compared to those inside a vehicle; results illustrated that the maximum SAR induced for mobile phone users in a vehicle is 5% higher than those in free space, but the SAR results showed no significant difference for the handedness. By comparing the SAR values between mobile phone users and nonusers inside a vehicle with a passenger count and seating locations, it was observed that the SAR values around the nonusers' body varied much in different situations, and were higher than those in free space, in some circumstances.

Index Terms—Electromagnetic compatibility, finite-difference time-domain (FDTD) method, specific absorption rate (SAR), vehicles, wireless communication device.

I. INTRODUCTION

IN recent years, there has been an extremely rapid increase in the use of wireless communication devices in our daily lives; these devices include smart phones, personal digital assistants, tablets, and notebook computers. At the same time, there has also been an expeditious growth of concern regarding possible adverse effects on human health from electromagnetic (EM) energy due to the use of wireless communication devices by the general public. A scientific evaluation of adverse health effects

of radio frequency (RF) energy around the human body was carried out by measuring the thermal change, within the safety limits given, based on specific absorption rates (SAR). In addition, restrictions on the radiation levels of consumer products were established. These include the International Commission on Non-Ionizing Radiation Protection guidelines [1] and IEEE C95.1 standard [2]; radiation limits in general defined in free space.

The evaluations of the SAR or the temperature elevation of the whole human body due to RF radiation are commonly conducted in a free space situation [3], [4]. In practice, wireless communication devices are not only used in open space, but are also frequently used in enclosed environments such as elevators, cars, trains, and airplanes. In such fully enclosed or semienclosed spaces, human exposure in terms of SAR is closely related to the EM field, which is multiplied, reflected, and scattered by the metallic walls of the enclosure. This could lead to complicated resonance effects, and therefore the SAR values induced in the human body would be altered in such enclosed or semienclosed environments. This possible argument of an EM field inside an enclosure has raised serious concerns among the general public [5].

The SAR values on a human body induced from wireless devices under an enclosed environment have been extensively investigated in the EM field. For instance, Simba *et al.* [6] reviewed and discussed some important parameters concerned with the effect of RF radiation due to the use of mobile phones in enclosed environments. They also concluded that the whole body average SAR values of both adult and children in elevators are nearly 50% larger than their corresponding values in free space. Likewise, Tang *et al.* [7], [8] conducted a computer simulation of EM field distributions induced from a mobile phone either inside fully or partially enclosed elevators. In comparison to free space, the findings displayed that the level of E-field strength would be increased by one-third if the mobile phone user was near the conducting wall of the elevators. For a semienclosed environment, Ruddle [9] has computed that the SAR values in a vehicle are due to external roof-mounted antenna and 900 MHz internal transmitters. Results indicated that the number and placement of occupants could vary in SAR values. Other simulations of the SAR value distributions due to a hands-free or a hand-held device operated at 835 MHz in a vehicle have been presented by Anzaldi *et al.* [10]. It was found

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*S.-W. Leung is with the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong (e-mail: eeswl@cityu.edu.hk).

Y. Diao, K.-H. Chan, Y.-M. Siu, and Y. Wu are with the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong (e-mail: yinliangdiao@yahoo.com; brian_chan@ieee.org; eeymsiu@cityu.edu.hk; wuyongle138@gmail.com).

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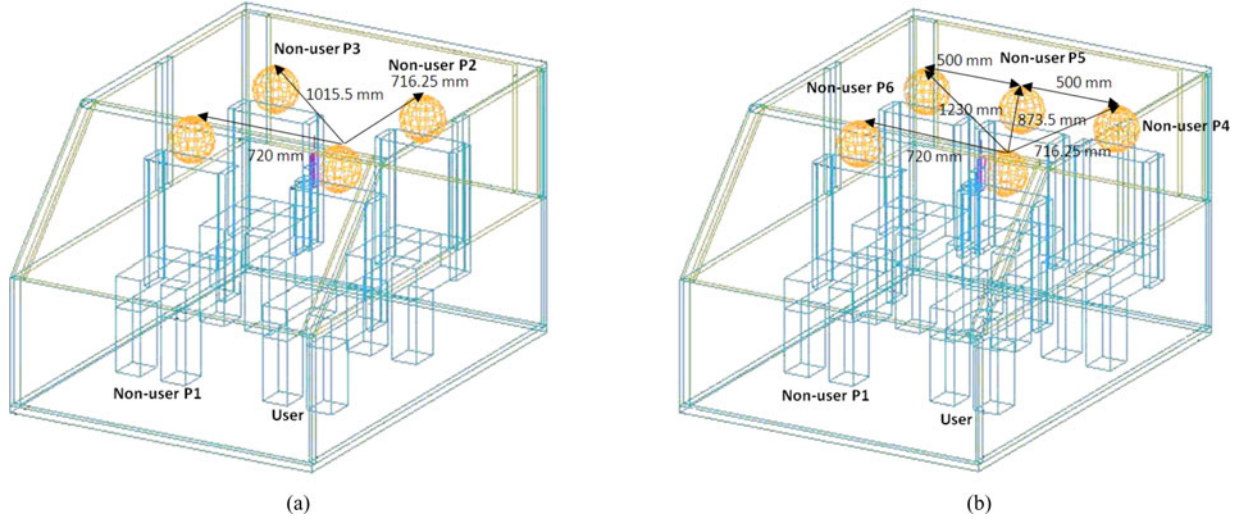


Fig. 1. Typical configuration of (a) four people, and (b) five people in a vehicle.

that the presence of the car body frame significantly changed the SAR distributions. Even in some cases of partial body exposure it was found that the SAR distributions were increased above the SAR limits as stated in current guidelines. The results implied that the changes were expectedly significant for the whole body exposure.

In response to the general concern over potential health effects of widespread EMF exposure, the World Health Organization [11] also set the study of various exposure scenarios for new and emerging RF technologies, and for changes in the use of established technologies to be high-priority research. This paper will therefore focus on the impact of mobile phone radiation inside a vehicle with different handedness, passenger count, and seating locations. In our study, the effect of a vehicle with an irregular boundary on EM energy absorbed by the homogeneous human body model was investigated. With the help of a numerically simulated model, accurate, and efficient evaluation of the SAR induced around the head and the body due to the use of wireless communication devices in such a semienclosed environment was carried out. The SAR induced around the user and nonuser has also been assessed herein. These simulation results were then directly compared to the situation of a person using a mobile phone in free space.

II. NUMERICAL MODELING

A finite-difference time-domain method (FDTD) modeling, which has been used throughout the study, can generally be formulated by two curl Maxwell's equations [12]. They are listed as follows:

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (1)$$

$$\nabla \times \vec{H} = -\varepsilon \frac{\partial \vec{E}}{\partial t}. \quad (2)$$

Based on the Yee's cells algorithm [12], numerical model can be derived from the aforementioned (1) and (2).

The numerical model in this study was simulated by means of commercial software, namely, Fidelity [13]. The FDTD modeling consists of $227 \times 299 \times 189 = 12\,827\,997$ cells. The largest cell was $8\text{ mm} \times 8\text{ mm} \times 8\text{ mm}$ while the smallest cell was $0.5\text{ mm} \times 0.5\text{ mm} \times 1\text{ mm}$ in the spatial domain. In the simulation model, the perfectly matched layer (PML) technique [14] was used for boundary condition, in which a fourth-order PML with a depth of six cells was constructed. The time step, Δt , was 1.056286 ps which satisfies the equation of the stability criteria,

$$\Delta t \leq \frac{1}{c_{\max} \sqrt{(1/\Delta x_{\min}^2) + (1/\Delta y_{\min}^2) + (1/\Delta z_{\min}^2)}} \quad (3)$$

where Δt was the time step; $\Delta x_{\min}$, $\Delta y_{\min}$, and $\Delta z_{\min}$ were the minimum space increments in x -, y -, and z -axes, respectively; and $c_{\max}$ was the maximum velocity in the simulation. The overall accuracy of the model was set to 0.1%, and the convergence of the simulation solutions have been checked for every 100 time steps, and the solutions are set to be converged for S-parameter extractions when the amplitude residual of the time signals are less than 0.001.

III. CONFIGURATION OF MODELING

The FDTD simulation model consisted of three items; the vehicle, the human model, and the mobile phone. Typical situations of four and five people sitting inside a five-passenger vehicle were modeled and are illustrated in 3-D view in Fig. 1. To characterize the EM analysis, only one of the passengers was designed to talk on a mobile phone (i.e., the user) at a fixed location for all the studied cases. The rest of the passengers were without any wireless communication device (i.e., the nonusers) and were named P1 to P6. All possible seating configurations of passengers were included in our study as shown in Fig. 2. In addition, the distances from the mobile phone user to all nonusers are summarized in Table I. In the modeling, the vehicle consisted mainly of vehicle casing and windows; the human model consisted of a head and body, and the mobile phone consisted

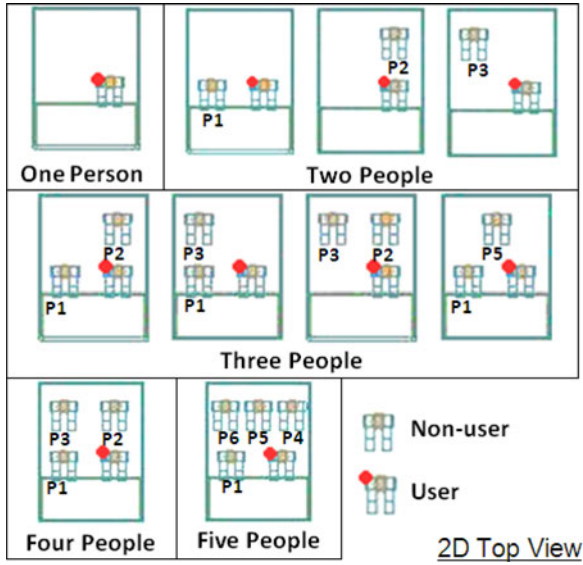


Fig. 2. Possible passenger configuration in the vehicle.

TABLE I
DISTANCE BETWEEN WIRELESS COMMUNICATION DEVICE USER AND NONUSERS IN VEHICLE

Non-user	Distance between user and non-user (mm)
P1	720
P2	716.25
P3	1015.5
P4	716.25
P5	873.5
P6	1230

TABLE II
DIELECTRIC PROPERTIES IN THE FDTD MODELING

Item	Relative Permittivity ϵ_r	Relative Permeability μ_r	Conductivity σ (S/m)	Density ρ (g/cm ³)
<i>Vehicle</i>				
Casing	1	1	1×10^7	1
Window	8	1	0	1
<i>Human</i>				
Head	41.5	1	0.97	1
Body	55	1	1.05	1
<i>Wireless Communications Device</i>				
Antenna & Casing	1	1	3.58×10^7	1
Inside Casing	2.6	1	0	1

of an antenna and casing. The details of dielectric properties of each item are presented in Table II.

A. Vehicle Model

Fig. 3 shows the configuration of the vehicle with an exterior dimension of $2.04 \text{ m} \times 1.54 \text{ m} \times 1.3 \text{ m}$; the vehicle was made of metal and glass. As the mobile phone radiation is propagated mainly within the interior parts of the vehicle casing, the front and the rear sections of the vehicle were not necessary and therefore not included in the simulation for the modeling. In

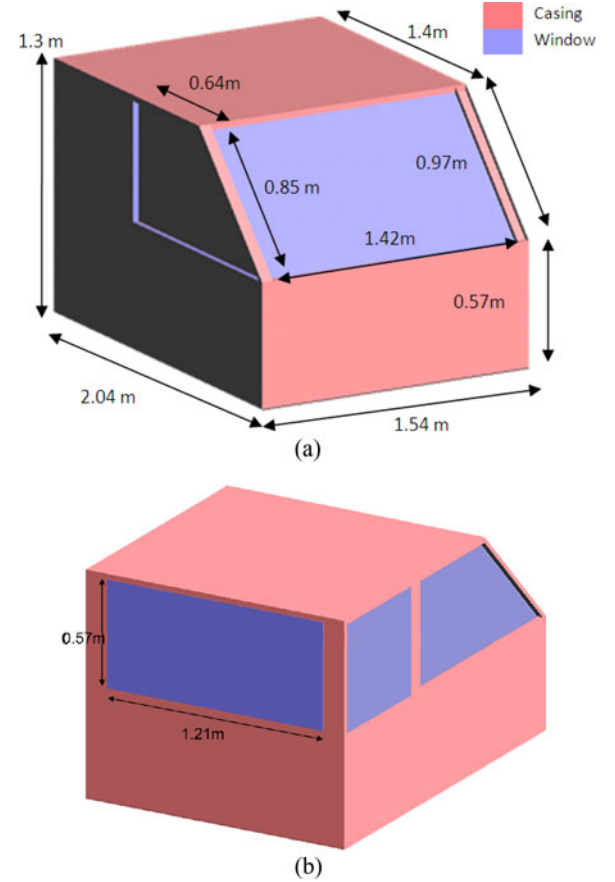


Fig. 3. (a) Front view, and (b) back view configuration of vehicle in the FDTD modeling.

addition, the removal of these parts saved more than 50% of simulation time and memory allocations.

B. Human Model

The human model used in the simulation is illustrated in Fig. 4. This model consists of a human head and body, and it is modeled to be seated in the vehicle based on an established human model [7]. Fig. 4 shows the dimensions of the human body, with the diameter of the human head being 200 mm. The dielectric properties of the human model fulfilled the recommended value from the FCC OET Bulletin 65 [15]; details for which are summarized in Table II.

C. Mobile Phone Model

The modeling of the mobile phone is shown in Fig. 5. The mobile phone mainly consisted of an antenna and casing, and it operated in GSM band at 900 MHz. The length of the antenna was 83 mm, which is a quarter wavelength of the frequency at 900 MHz; the dimension of the casing was $20 \text{ mm} \times 40 \text{ mm} \times 150 \text{ mm}$. The mobile phone was mainly made of copper filled with plastic material. For the excitation of the mobile antenna, a coaxial feeding technique [13] by constructing an enclosed port at the antenna feeding position was used in the

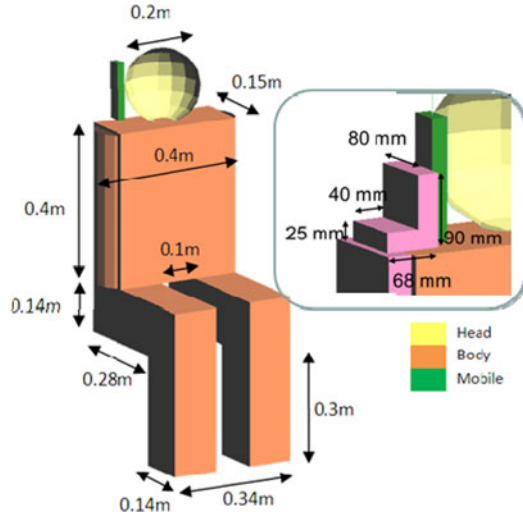


Fig. 4. Configuration of human model in the vehicle in the FDTD modeling.

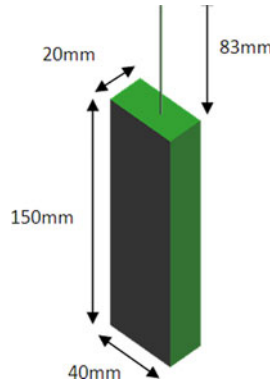


Fig. 5. Configuration of 900 MHz mobile phone in the modeling.

FDTD simulation; the output radiation power was set to 2 W for modeling the worst-case scenario in mobile communications.

IV. RESULTS AND DISCUSSION

In this section, the return loss of the mobile phone antenna and SAR values for the user and nonusers are presented. The results for the case of one person in free space and the cases of different human capacities up to five passengers in the vehicle are also discussed.

A. Return Loss

The S-parameter with reference impedance of 50Ω has been calculated after obtaining enough convergence from the simulations. The comparison on the results of return loss (S_{11}) of the mobile phone when being used in free space and different passenger counts in the vehicle is shown in Fig. 6. Results have shown that the resonant frequency of the mobile phone operated at 900 MHz had a maximum of about 8 dB in magnitude for S_{11} . It was found that when the mobile phone is operating within this semienclosed environment with different human loadings, the return loss of the antenna is not particularly affected, and there is no shift in the resonant frequency.

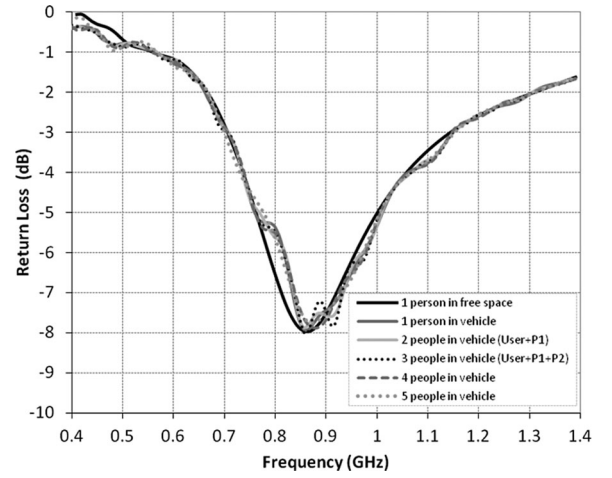


Fig. 6. Comparison of return loss of people using mobile phone in free space and inside vehicle.

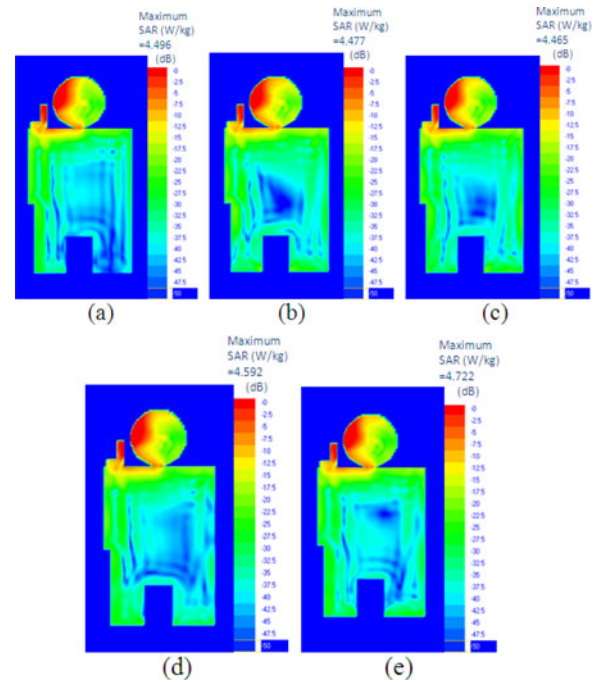


Fig. 7. SAR distributions for mobile phone user in (a) free space, (b) vehicle with one person, (c) vehicle with two people (User + P1), (d) vehicle with three people (User + P1 + P2), and (e) vehicle with four people.

B. Abstract

The maximum SAR values for the user and nonusers in all the studied scenarios are presented in this part. As the SAR value is more prominent at the mobile phone user, the spatial-average SARs of all users is also included in the studies.

1) *Comparison of the Mobile Phone User in Free Space, and in the Vehicle With Different Passenger Counts:* Fig. 7 illustrates the SAR distributions of the mobile phone user in free space, and in the vehicle with different numbers of passengers. Results indicate that the “hot spot” of the SAR value is located at the human head and hand. Results also show that the SAR distribution in the mobile phone user’s body is only affected by a slight

TABLE III
COMPARISON OF SAR VALUE FOR FREE SPACE AND DIFFERENT PASSENGER COUNTS SITUATIONS

	Max. SAR (W/kg)	Peak SAR avg. over 10g (W/kg)	SAR variation compare to free space	
			Max. SAR	Peak SAR avg. over 10g
1 person in free space	4.496	2.862	-	-
1 person in vehicle	4.477	2.889	-0.42%	+0.94%
2 people in vehicle	4.465	2.986	-0.69%	+4.33%
3 people in vehicle	4.592	2.958	+2.14%	+3.35%
4 people in vehicle	4.722	3.049	+5.03%	+6.53%
5 people in vehicle	4.590	2.941	+2.09%	+2.76%

increase or decrease of the SAR value by a few percentages. In Fig. 7(e) and Table III, results illustrate that the maximum SAR and the peak averaged SAR values for the mobile phone user sitting inside the vehicle are 4.722 and 3.049 W/kg, respectively. The SAR values found in the vehicle are about 5% higher than that of the free space situation. The slight increase or decrease of the maximum SAR is mainly due to the complication of the EM distribution including reflecting, scattering, and standing waves exist at metallic walls inside the vehicles. In Table III, the peak averaged SAR for the mobile phone user in the vehicle is higher than that of in free space, which is in accordance with expectation that the increase of SAR values is mainly due to the internal reflections of an EM wave from the windows and the metallic casing of the vehicle.

2) *Comparison of Handedness in Mobile Phone Usage in the Vehicle With Different Passenger Counts*: Fig. 8 shows the comparison of the SAR distributions of handedness in mobile phone usage in the vehicle with one person. The results show that the maximum SAR value of a left-handed mobile phone user is 4.513 W/kg, which is 0.8% higher than that of a right-handed mobile phone user; this implied that the SAR distributions are slightly different for different handedness. In addition, the comparison of maximum SAR values between users of different handedness in the cases of different passenger counts is illustrated in Table IV. Results indicate that the differences of SAR values between users of different handedness are not significant. From the obtained results in Table IV, the percentage difference on the SAR value of a left-handed user is up to 6.25% when compared to a right-handed user. For the cases of one person and two people in the vehicle, the percentage difference is generally small. When the number of passengers is increased from 2 to 5 passengers, the percentage difference in handedness can be increased from 0.8% to 6.25%. The results have indicated that the SAR induced to the passengers could also be affected by the passenger count, and will be discussed in the next section in detail.

3) *Comparison of Passenger Counts in the Vehicle*: Due to the fact that the difference of the SAR values induced by different handedness is not significant, the effect of the SAR due to a right-handed user is therefore presented here. A comparison of the SAR distributions for mobile phone nonusers in the vehicle with 2 to 4 passengers is illustrated in Fig. 9. Results show that SARs in nonusers are mainly induced in the head and

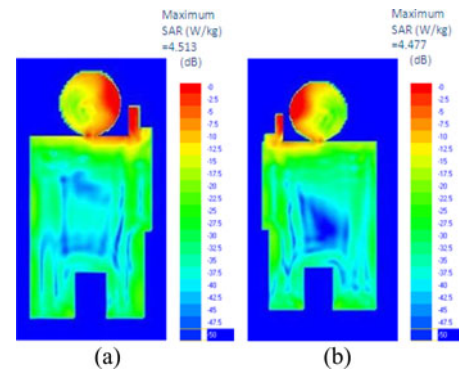


Fig. 8. Comparison of SAR distribution for (a) left-hand and (b) right-hand mobile phone user in vehicle with one person.

TABLE IV
COMPARISON OF SAR VALUE FOR LEFT HAND AND RIGHT HAND SITUATION IN FREE SPACE AND IN VEHICLE

	Max. SAR (W/kg)		Peak SAR avg. over 10g (W/kg)		SAR variation due to the handedness	
	Left hand	Right hand	Left hand	Right hand	Max. SAR	Peak SAR avg. over 10g
1 person in free space	4.513	4.496	2.969	2.865	+0.38%	+3.64%
1 person in vehicle	4.513	4.477	2.988	2.889	+0.80%	+3.31%
2 people in vehicle						
User + P1	4.497	4.465	2.984	2.986	+0.72%	-0.07%
User + P2	4.514	4.507	2.987	2.899	+0.16%	+3.04%
User + P3	4.600	4.772	3.049	3.136	-3.60%	-2.77%
3 people in vehicle						
User + P1 + P2	4.373	4.592	2.890	2.958	-4.77%	-2.30%
User + P1 + P3	4.476	4.681	2.976	3.008	-4.38%	-1.06%
User + P2 + P3	4.523	4.687	2.992	3.027	-3.50%	-1.16%
User + P1 + P5	4.379	4.540	2.904	2.950	-3.55%	-1.56%
4 people in vehicle	4.427	4.722	2.948	3.049	-6.25%	-3.31%
5 people in vehicle	4.443	4.590	2.949	2.941	-3.20%	+0.27%

the shoulders; results also indicate that the induced SAR in the human body is affected by the passenger count. Table V also shows that the range of maximum SAR value induced in the human body of nonusers is between 0.05 and 0.187 W/kg. The maximum SAR values for nonusers are only 1% to 4% different to that of the mobile phone user. For nonusers, it was found that in various situations, the maximum SAR values of nonusers P1 and P3 are higher than that of nonusers P2, P5, and P6, and the maximum SAR value induced in nonusers P1 and P3 can be up to 0.152 and 0.187 W/kg, respectively. The differences of the SAR values induced in nonusers are expected to be as a result of the internal reflections inside the vehicle and different distances between the user and nonusers.

4) *Comparison of Different Seating Configurations in the Vehicle*: In addition to the typical seating configurations for different passenger counts, a number of seating configurations were also investigated. Results indicate that the SAR is usually induced inside, or near the surface of the human body, as indicated in Fig. 10. The findings also suggested that the SAR “hot spot” induced in both the mobile phone users and nonusers

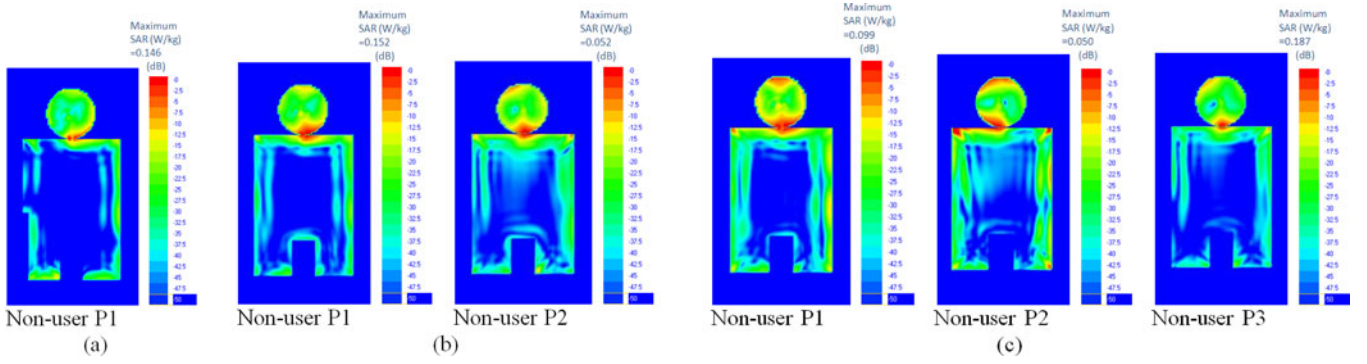


Fig. 9. SAR distributions for mobile phone nonusers in (a) vehicle with two people, (b) vehicle with three people, and (c) vehicle with four people.

TABLE V
COMPARISON OF MAXIMUM SAR VALUE FOR MOBILE PHONE USER AND NONUSERS

	Maximum SAR (W/kg)	Percentage of Max. SAR in Nonusers when compare to Max. SAR in User
1 person in vehicle		
User	4.477	-
2 people in vehicle		
User	4.465	-
P1	0.146	3.3%
3 people in vehicle		
User	4.592	-
P1	0.152	3.3%
P2	0.052	1.1%
4 people in vehicle		
User	4.722	-
P1	0.099	2.1%
P2	0.050	1.1%
P3	0.187	4.0%
5 people in vehicle		
User	4.590	-
P1	0.082	1.8%
P4	0.044	1.0%
P5	0.051	1.1%
P6	0.064	1.4%

TABLE VI
COMPARISON OF SAR VALUE FOR PEOPLE IN DIFFERENT SEATING LOCATIONS IN VEHICLE (TWO PEOPLE AND THREE PEOPLE)

	Max. SAR (W/kg) (Percentage of SAR value compare to the user)					Percentage of Max. SAR in Nonusers compare to Max. SAR in User
User	P1	P2	P3	P5		
2 People						
User+P1	4.465	0.146 (3.43%)	-	-	-	3.43%
User+P2	4.507	-	0.062 (1.38%)	-	-	1.38%
User+P3	4.772	-	-	0.143 (3.00%)	-	3.00%
3 People						
User+P1+P2	4.592	0.152 (3.31%)	0.052 (1.13%)	-	-	3.31%
User+P1+P3	4.681	0.171 (3.65%)	-	0.118 (2.52%)	-	3.65%
User+P2+P3	4.687	-	0.053 (1.13%)	0.233 (4.97%)	-	4.97%
User+P1+P5	4.540	0.067 (1.48%)	-	-	0.068 (1.48%)	1.48%

is generally located at the head and the shoulders. Meanwhile, another SAR “hot spot” was found to be induced at the hand that the user holds the mobile phone with. A comparison between the maximum SAR value induced in the mobile phone user and passengers for different seating configurations is also summarized in Table VI and Fig. 10. Results indicate that the maximum SAR value induced in the passengers can be up to 0.233 W/kg (in the User + P2 + P3 case), which is about 5% of the mobile phone user. The SAR values of nonusers are much smaller than that of the mobile phone user.

V. MODEL VALIDATION

The simulation results have been validated and compared to various published papers [10], [16], [17]. We set the output power of the monopole antenna from 2 W to 600 mW, which is in-line with the output power described in these papers. Our calculated peak SAR for one person in free space situation

is $0.3 \times 4.496 \text{ W/kg} = 1.349 \text{ W/kg}$. When compared with a similar study by Chen *et al.* [16], their calculated peak SAR is 1.48 W/kg, is consistent with our result.

Also, our calculated peak averaged SAR over 10 g located at 23 mm away from the monopole antenna position is $0.3 \times 2.862 \text{ W/kg} = 0.859 \text{ W/kg}$. Similarly, as presented in [17], a higher peak averaged SAR over 10 g of 1.3 W/kg has been obtained at a shorter distance of 12 mm away from the antenna feeding position. The lower value of the calculated peak averaged SAR obtained in our case is reasonable.

As reported in [10], the peak SAR is about 2 W/kg at 9 mm away from the right ear for the front passenger using a mobile phone in the vehicle. Our calculated peak SAR over 10 g is $0.3 \times 4.477 \text{ W/kg} = 1.343 \text{ W/kg}$ at 23 mm away from the antenna position in the head position under similar situation. The lower value of the peak SAR value is also found to be reasonable and comparable to others studies.

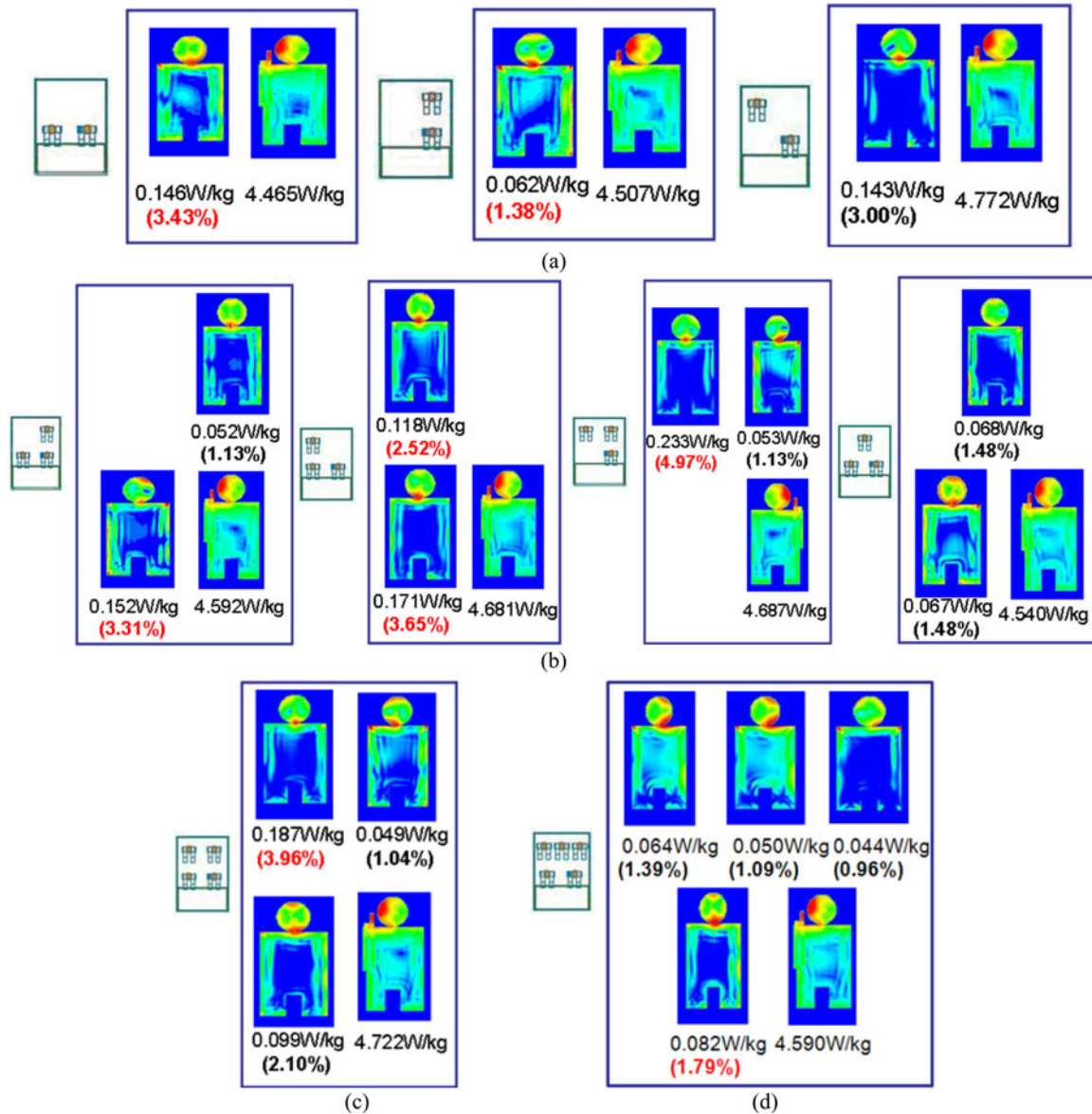


Fig. 10. SAR distributions for different seating configurations in vehicle in the situation of (a) two people, (b) three people, (c) four people, and (d) five people.

VI. CONCLUSION

The investigation of the SAR induced in the human head and body due to EM radiation of a mobile phone inside a vehicle was carried out. Results show that the maximum SAR value induced in the mobile phone user inside a vehicle increased by 5% in comparison to the use of a mobile phone in free space. Results also illustrate that the highest SAR is mainly located at the head and shoulder positions of the human body in all presented cases. It was also observed from the study that the difference of the SAR values between variations in handedness is insignificant. The findings demonstrated that the change of passenger count inside the vehicle can alter the maximum SAR value induced in the bodies of passengers. In addition, when a passenger sits next to a mobile phone user, the maximum SAR value of that passenger can be up to about 5% of that of the mobile phone user in some situations. Consequently, it can be concluded that the induced level of the SAR value to the

nonuser is directly related to the distance between the user and nonusers.

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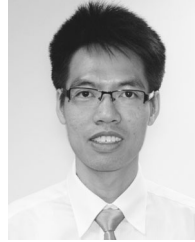
Sai-Wing Leung (M'83–SM'03) was born in Hong Kong, and received the first degree in electrical engineering at the City University, London, U.K., in 1976. He received the Ph.D. degree in 1981 from the City University.

In 1982, he joined the Engineering Division of ERA Technology, Ltd., in U. K., as a Senior Engineer; he joined Hirst Research Centre, GEC Research Company, Ltd., as a Principal Engineer, in 1984, and was responsible for leading a project on the development of electromagnetic launchers for armour-piercing applications. In 1985, he joined the Weapon Department of Thorn EMI Electronics, Ltd., and was responsible for the development of the Radar tracking of the multilaunch rocker system. In 1988, he moved to the U.S. joining Martin Marietta Aerospace in Orlando, working on the same system. In the same year, he joined the City University of Hong Kong (CityU) as a Senior Lecturer, and at present he is an Associate Professor in the Electronic Engineering Department, and a Team Member of the Applied Electromagnetics Laboratory. He is actively involved in numerous consultancy projects assisting industry, in both Hong Kong and overseas, in solving electromagnetic compatibility/electromagnetic interference problems. Dr. Leung is the Director of EMC Consulting Group of CityU Professional Services, Ltd. He is an Assessor of the Hong Kong Laboratory Accreditation Scheme (HoKLAS) on EMC area, and a Member of the working party on Electrical and Electronic Products, Accreditation Advisory Board, Innovation and Technology Commission, Government of Hong Kong SAR. He is also the founding Chairman of EMC Hong Kong Chapter of the IEEE Hong Kong Section.



Yinliang Diao (S'12) received the B.E. degree from the Chongqing University, Chongqing, China, in 2008, and the Master's degree in electronic engineering from the Beijing University of Posts and Telecommunications, Beijing, China, in 2011.

He is currently a Research Assistant in the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong. His research interests include electromagnetic compatibility, electro-magnetic field and microwave technology, and electromagnetic field simulation.



Kwok-Hung Chan (S'02–M'05) received the B.Eng. degree (with first class Hons.) in electronic engineering, and the M.Phil. and Ph.D. degrees from the City University of Hong Kong (CityU), Kowloon, Hong Kong, in 2001, 2004, and 2008, respectively.

In 2004, he was a Research Assistant in the Wireless Communications Research Centre, CityU, where he is currently a Research Fellow in the Department of Electronic Engineering. His research interests include human safety and biomedical issues in electromagnetic compatibility, bio-electromagnetics, and

electrostatic discharge.

Dr. Chan is the Vice-Chairman of the IEEE Electromagnetic Compatibility Chapter in Hong Kong.

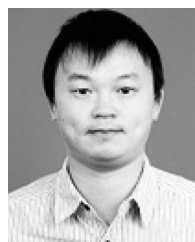


Yun-Ming Siu received the B.Sc. degree in 1981 from the University of Manchester, Manchester, U. K. and the Ph.D. degree from the University of Hong Kong, Kowloon, Hong Kong, in 1996.

From 1981 to 1989, he was at Racal-BCC, U.K., first as a Development Engineer, and then a Principal Engineer responsible for the development of tactical communications systems. In 1990, he joined City University of Hong Kong, Kowloon, Hong Kong, where he is currently an Associate Professor in the Department of Electronic Engineering. His current

research interests include spread-spectrum techniques, electromagnetic compatibility, and information and communication networks.

Dr. Siu was the Chairman of the Consumer Electronics Chapter of the IEEE Hong Kong Section in the years 1998 and 1999.



Yongle Wu received the B.Eng. degree in communication engineering and the Ph.D. degree in electronic engineering from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2006 and 2011, respectively.

During April to October in 2010, he was a Research Assistant at the City University of Hong Kong (CityU), Kowloon, Hong Kong. In 2011, he joined the BUPT and became a Lecturer in the School of Electronic Engineering in BUPT. Since June 2012, he is also a Senior Research Associate at CityU. His

research interests include generalized Smith charts, generalized transmission lines, and dual-frequency components design.